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(54) MULTISTAGE DETECTION OF VELOCITY
 ESTIMATION FROM SEISMOGRAMS

(71) We, MOBIL OIL CORPORATION, a corporation organised under the laws of the State of New York, United States of America, of 150 East 42nd Street, New York, New York 10017, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to the estimation of acoustic velocity from a set of seismic traces and more particularly to a two-stage estimation process.

In seismic exploration the measurement of velocity is generally considered the major parameter in the processing and interpretation of seismograms. The determination of the acoustic velocity characteristics of the earth from seismograms is described in "Seismic Velocities from Surface Measurements", C. H. Dix, *Geophysics*, Vol 20, pages 68—86, 1955. In general, acoustic velocity is determined from seismograms by the following relationship:

$$t_x = \left(T_0^2 + \frac{X_N^2}{V^2} \right)^{1/2} \pm \Delta t$$

In the foregoing, t_x is the reflection time on a seismogram trace recorded using a detector spaced a distance X_N from the source, V is the acoustic velocity, T_0 is the zero offset time, and Δt is the dip between common reflection points on the subsurface interface producing the reflection.

One type of field technique which produces sets of traces in which the reflection times follow the above relationship is commonly referred to as common depth point or common reflection point seismic exploration.

According to the present invention we provide a method of determining velocity from sets of seismic traces representing the reflections of seismic energy produced from a plurality of spaced sources and reflected from

subsurface interfaces comprising the following steps each performed on automatic computing apparatus:

performing a first stage search by detection of signals at points on traces to determine the reflection times and acoustic velocity characteristics of the subsurface interfaces, and performing a second stage search, by detection of signals in selected time windows in the seismic traces, for acoustic velocity at the reflection times determined in the first stage search and with a velocity range centred on the acoustic velocity determined in the first stage search.

In accordance with an embodiment of this invention, a point estimation technique is used to obtain a first estimate of reflection time, velocity, dip, and amplitude. The data is again processed at the time and within a range of velocities centred on the velocity determined from the first estimate. A window estimation technique is used in the second stage to improve the velocity estimate.

The first stage of detection reduces the time and velocity range and has the advantage of high speed and good time resolution. The second stage of detection incorporates the good signal-to-noise ratio properties of estimates obtained by a window detection technique, at the reflection times and centred at the velocities determined from the first estimation process.

In accordance with a preferred feature of the invention, the dip is determined by a linear search of amplitudes in the first stage of estimation. These dips are used in the second stage window type estimation.

The invention further provides a record of the acoustic velocities determined in the second stage search of the method.

The advantages and features of the invention will be better understood from the following more detailed description given with reference to the accompanying drawings.

Description of the Drawings.

Figure 1 depicts a set of seismic traces;

Figures 2A, 2AA and 2B are flow sheets depicting the performance of the process on a general purpose digital computer;

Figure 3 depicts an output from an intermediate stage in the process;

Figure 4 depicts a set of amplitude traces, one for each common depth point (CDP) set;

Figure 5 depicts a set of seismic traces used in the window estimation; and

Figure 6 is a plot of signal power.

Referring to Fig. 1, there is shown a set of seismograms, $S_1, S_2 \dots S_1 \dots S_n$. As is the usual practice, these seismograms are digitized so that values at periodic sample times (indicated on the trace S_n by the vertically spaced dots) represent reflections of seismic energy. The seismic energy is produced from a plurality of spaced sources and reflected from subsurface interfaces. The abscissa in Fig. 1 represents horizontal distance along a line of exploration. Sources of seismic energy and detectors for detecting the reflected seismic energy are spaced along the line of exploration. In Fig. 1, X_1 is the horizontal distance of the detector (i.e. seismometer) producing trace S_1 , X_1 is the horizontal distance of the seismometer producing the trace S_1 , and so on.

The zero offset times for this set of traces are the theoretical times of reflections for reflection points directly beneath the source, at the location denoted X_0 . The zero offset times of T_{01} and T_{02} have been denoted in Fig. 1. Ignoring dip, the times of reflections across this set of traces are described by:

$$(\Delta T)^2 = \frac{X^2}{V^2} - 2T_0 \Delta T$$

where T_0 is the zero offset time, T is the time of a reflection on a particular trace, X is the horizontal offset distance associated with that trace, and ΔT is the time shift of the reflection to that trace. Stated another way, the times of reflection across the set of traces are specified by a hyperbolic travel time curve, the shape of which depends upon the acoustic velocity of the earth. Two hyperbolic curves have been drawn across the set of traces in Fig. 1 to show the expected time of arrival of a particular reflection for two different assumed values of velocity V_1 and V_2 .

The flow sheet of the first stage of this process is shown in Fig. 2A. The inputs to the system include sets of common depth point traces, each set including traces $S_1 \dots S_n$. Also applied as inputs to the system are the limits of the range of expected velocities, the range being defined by the limits V_1 and V_2 . Another input to the system is the threshold α against which the signal power of reflections is compared to

determine whether a reflection exists along a particular travel time curve.

The first two indicated steps are used to start the computation of travel time curves, for a particular zero offset time from samples on the last trace. As indicated at 20, the time shift ΔT to the far trace S_n is computed for the velocity V_2 . As shown in Fig. 1, this ΔT occurs at the point 21 on the trace S_n . That is, the travel time curve does not fall on a sample of the far trace S_n . Therefore, the routine selects the ΔT corresponding with the sample occurring at 22 in Fig. 1. The selection of this ΔT that falls on the sample 22 is indicated at 23 in the flow sheet. Using this ΔT , the actual velocity for that travel time curve can be computed. Then, the ΔT for each of the other traces, $S_1 \dots S_1 \dots S_{n-1}$, can be computed. This specifies a travel time curve:

$$(\Delta T)^2 = \frac{X^2}{V^2} - 2T_0 \Delta T$$

Then, other travel time curves are computed for other samples on the trace S_n . For example, the travel time curves which intersect S_n at the sample times 24, 25, and so on, are each computed. The computations of these travel time curves are indicated at 26 and 27 in the flow sheet. As indicated at 27, the computation of travel time curves is iterated for velocities in the range V_1 to V_2 . For example, there may be 100 travel time curves in the index set thus formed.

For this index set of travel time curves, the velocity associated with each curve is computed for different iterated zero offset times, as indicated at 28. That is, the same curvature ΔT is retained but T_0 is larger. Therefore, the associated value of velocity is smaller. This approach permits the calculation of an index set for signal detection once, or at most a limited number of times, for each record.

It should be noted that it will probably not be possible to use the same index set of travel time curves over the full length of the records. The range of velocities will change for each sample time. For example, assume that the range for zero offset time T_1 was $V_1=12,000$ feet per second and $V_2=5,000$ feet per second. For the zero offset time T_2 , the range might change to 4,751 to 9,275 feet per second. At some later record time, the range of velocities associated with the index set may not encompass the actual range of velocities expected in that area. Therefore, at this point, there must be a recomputation of the travel time curves. It is possible that three or more index sets of travel time curves may be used over the full record length. In practice, an index set is computed each 25

samples so that an a priori $V(t)$ can be followed with a small number of travel time curves.

Reflections in the traces are detected along the curved lines of the index set. One particular signal detection technique which can be used is to sum the samples from each trace along one of the curved lines. For example, referring to Fig. 1, the sum is formed of the value at the sampling time 29 on the first trace, the sampling time 30 on the second trace, the sampling time 31 on the i th trace, the sampling time 24 on the n th trace, and the values at the sampling time on intermediate traces specified by that travel time curve. This sum indicates the signal power of reflections along that line. A similar sum is formed along each of the curves in the index set. This summation of the traces along the travel time curves is indicated at 33 in Fig. 2A.

The sums are compared to determine the travel time curve associated with the maximum reflection signal power. The acoustic velocity V_N associated with the travel time curve so identified is selected as the acoustic velocity at a particular record time T_N .

Next, a determination of whether an actual reflection exists at this record time is made. This is done by comparing the sum to the threshold α . The search for sums exceeding α is indicated at 34 in the flow sheet. Where the sum exceeds the threshold α , the value of velocity V_N is stored together with the time T_N . Also stored is horizontal position X of the CDP set. The storage step is indicated at 35.

A portion of a plot produced from the stored values at 35 is shown in Fig. 3. The plotting step is indicated at 36 in the flow sheet. In this plot, the abscissa is horizontal distance between common depth point sets and the ordinate is record time. For example, at the record time t_1 , the velocity 4900 feet per second is plotted for the CDP set at the extreme right. At the time t_2 , the velocity 4700 is plotted for this CDP set. At the time t_3 , the velocity 4800 is plotted for this CDP set.

For the next CDP set to the left, the velocity 4800 is plotted at time t_1 , the velocity 4700 is plotted at the time t_2 , and the velocity 4800 is plotted at the time t_3 .

The steps described thus far are the first stage of detection. Detection in the manner just described along travel time curves is commonly referred to as a point estimation technique. Such a technique has the advantage of high speed and extremely accurate estimates of the times T of reflections.

The steps of the first stage of estimation are described in more detail in our Specification 1 304 248. The amplitude of each of the sums of the traces for each CDP set is stored. There is an amplitude trace for

each CDP set. Fig. 4 is an analog representation of a set of the amplitude traces. The storage of the amplitude traces is indicated at 37 in the flow sheet of Fig. 2AA. A linear search is performed on these amplitude traces along each of a plurality of assumed dip lines. In Fig. 4, dip lines of 0, 1, 2, 3, 4 and 5 milliseconds have been indicated. This search includes a signal detection operation along each of these dip lines, for example, a simple summing of the amplitude traces along each of the dip lines is one signal detection operation. As can be seen, the dip line of 3 milliseconds produces the largest sum. This is the determined dip D_n of the subsurface interface for the reflection at the time T_{FIRST} . Similar searches are performed to determine the dip at the other detected reflection times. The search along various dip lines is indicated at 38 in the flow sheet.

The outputs from the first stage of the process are the reflection times T_n , the velocities V_n , and the dips D_n . Assuming there are M detected reflections, these are $T_{FIRST}, T_{SECOND} \dots T_M; V_{FIRST}, V_{SECOND} \dots V_M; D_{FIRST}, D_{SECOND} \dots D_M$. Also, the CDP sets of traces are inputted to the second stage. One set of these traces is depicted in analog form in Fig. 5. The second stage of estimation is similar to the process described in our Specification 1 282 936.

A time window of the seismic trace is selected at different given values of travel time. For example, at the travel time T_{FIRST} , a seismic time window between the points 39 and 40 (Fig. 5) is selected.

The window selected on the remaining traces in the suite is determined using an assumed velocity V_1 .

The corresponding travel time, referred to as t_x , on the remaining traces is calculated as will be subsequently described. Windows on these traces are selected, the window between the points 41 and 42 being selected for trace 24, for example. The signal in these windows is detected. Many signal detection techniques are suitable for use in the present invention and their use is within the scope of the invention. Signal detection is described, for example, in "Statistical Theory of Signal Detection", Carl W. Hellstrom, Pergamon Press, 1961. The particular form of detection described herein is a zero lag cross-correlation between the selected windows. In general, a function indicative of the presence of a signal is detected. In the cross-correlation technique, the signal power is detected.

Next, a different value of velocity, V_2 , is assumed and the same operation is performed. Windows on each trace are selected, the selection being indicated by the limits of the lines 43 and 44. Again the signal power of all of these windows is detected. The search continues through all values of

velocity in a given range. For example, a value of velocity V_s is assumed and windows within the limits of the lines 45 and 46 are selected. The signal power of these windows is detected and stored.

It will be apparent that the signal power will be a maximum for the correct value of assumed velocity. This is best demonstrated in Fig. 6 which shows a plot of signal power as a function of assumed velocity for the time T_{FIRST} . The peak in the signal power indicates the velocity for the seismic event.

A velocity search with the foregoing window estimation technique is performed at each of the times T_{FIRST} , T_{SECOND} ... T_M . The velocity searches are performed within a range which is centered on the velocity determined in the first stage of detection.

While the range of searched velocities and the increments in the velocity differ depending upon the particular type of seismograms being processed, one example of suitable values is as follows. A range of velocity from 5,000 to 9,800 feet per second was searched at velocity intervals of 200 feet per second.

The length of the window selected should correspond to the expected length of a seismic wavelet in the seismogram. For example, a window 40 milliseconds length is generally suitable.

The second stage of the process of the present invention can now be described in more detail with reference to the flow sheet of Fig. 2B.

As indicated at 47, the travel time t_x for each of the traces in the suite is calculated. The travel time for the first trace is assumed to be T_{FIRST} . For each of the other traces, the travel time is given by:

$$t_{xn} = \left(T_0^2 + \frac{X_n^2}{V_{FIRST}^2} \right)^{1/2} \pm \Delta T_{FIRST}$$

ΔT represents the dip between sets of CDP traces and is held fixed within each suite of CDP traces when computing t_{xn} for traces in that suite. For the calculation of the travel time for the second trace, the value of X_n in the above is the horizontal distance between the source and the seismometer from which the second trace was obtained. A similar determination is made for the travel time t_{xn} for each trace.

Then, as indicated at 48, a window of given length is selected from each seismogram.

These windows from the respective traces are used in the determination of the zero lag cross-correlation signal power between the traces as indicated at 49. While such correlation detection is a particularly good technique for detecting signal in the presence of noise, other signal detection techniques may be used. For example, the amplitude of the windows

could be added together sample by sample to form an output-representing signal.

In the cross-correlation technique, each sample in the window is multiplied by the corresponding sample in all of the other windows and the products are summed. This type of cross-correlation differs from the usual type of cross-correlation used in seismic processing in that there is no time shifting of the inputs being correlated. That is, there is a straight-forward multiplication point by point of the samples in each window. For each velocity in the velocity search there will be $1/2 (L-1)$ cross-correlation products to be summed where L is the number of traces. Where L is 24, as in the example under consideration, the total number of cross-correlation products is 276.

The computed value of signal power is stored as indicated at 50 in Fig. 1.

Next, the value of velocity is incremented as indicated at 51. The steps 47—50 are performed for the new incremented value of velocity. These steps are performed for each iterated value of velocity in a range which is centered on V_{FIRST} . As indicated at 52 the maximum in the signal power determines the velocity of the seismic event. This determined velocity is designated V_{NEW} . As indicated at 53 this value of V_{NEW} is stored together with the time of the reflection T_N , the dip of the reflection D_N and the amplitude of the reflection A_N . Then the travel time T is incremented to T_{SECOND} and all of the steps 47—53 are performed again for the second reflection detected by the first stage of processing. This is repeated for each of the M detected reflections.

As an important part of the process, the travel times t_x calculated in accordance with the step 47 incorporate the dip determined from the first stage of estimation. Because of this, good velocity estimates are obtained in the second stage in the presence of dip. This improvement also produces better results in low signal-to-noise ratio areas.

In the calculation of the values of t_x for each trace an additional component is added. This additional component is the calculated value of time shift from CDP set to CDP set for the value of dip determined from the first stage of estimation.

Where CDP sets of seismograms are being processed, the travel times t_x are generated in accordance with:

$$t_x = \left(T_0^2 + \frac{X^2}{V^2} \right)^{1/2} \pm \Delta t$$

From the foregoing description a skilled programmer will be able to program a general purpose digital computer to carry out the process. While many general purpose digital computers are suitable for use in performing

the process of this invention, one computing system which is particularly suitable is supplied by the Control Data Corporation under the general model designation 6600.

In our Specification No. 1,282,936 we claim:— A method of determining the seismic velocity characteristics of the earth from a suite of seismograms representing the reflection of seismic energy from reflecting points in the earth, different seismograms of said suite of seismograms being obtained from respective detectors spaced along a line of exploration, comprising automatically processing said seismograms in a data processing machine as follows:

- (a) for a given value of vertical travel time T_0 , and assumed seismic velocity V , generating in said data processing machine physical representations of the corresponding travel time t_x for each of the traces in said suite of seismograms, said times t_x having time shifts from trace to trace corresponding with the assumed value of velocity;
- (b) for each value of t_x generated in step (a), selecting a respective window of each trace, said window commencing at t_x and having a time length which approximates the expected length of a seismic wavelet in said seismograms;
- (c) detecting the presence of a seismic signal in the windows across said traces;
- (d) repeating steps (a) to (c) in said data processing machine for different values of assumed velocity V , and for different values of travel time T_0 .

In our Specification No. 1,304,248 we claim:— A method of processing seismic traces representing reflections of seismic energy produced from a plurality of spaced sources and reflected from subsurface interfaces, utilizing automatic computing apparatus, comprising detecting signals in each of a plurality of said traces along several travel time curves each computed for one of a range of assumed acoustic velocities, selecting the acoustic velocity corresponding to maximum detected signal and plotting the alpha numeric representation of the selected acoustic velocity upon a chart of horizontal earth surface distance *versus* record time.

WHAT WE CLAIM IS:—

1. A method of determining velocity from sets of seismic traces representing the reflections of seismic energy produced from a plurality of spaced sources and reflected from subsurface interfaces comprising the following steps each performed on automatic computing apparatus:

performing a first stage search by detection of signals at points on the seismic traces to determine the reflection times and acoustic velocity characteristic of the subsurface interfaces, and

performing a second stage search, by detection of signals in selected time windows in the seismic traces, for acoustic velocity at the reflection times determined in the first stage search and with a velocity range centred on the acoustic velocity determined in the first stage search.

2. A method according to Claim 1, wherein the sets are CDP sets, characterised in that the CDP traces are stacked and the first stage search includes storing the amplitudes of the stacking results at the reflection times determined in the first stage search, and searching said amplitudes along various assumed dip lines to determine the dip of the subsurface interfaces producing each of the detected reflections.

3. A method according to Claim 2, characterised in that the second stage search is performed with the dip determined in the first stage search.

4. A method according to any of claims 1 to 3, characterised in that the first stage search includes:

- (a) detecting reflections in CDP traces along hyperbolic travel time curves for different, iterated, zero offset sampling times;
- (b) computing the velocity associated with each travel time curve along which a reflection is detected;

and that the second stage search includes:

- (c) for each zero offset sampling time for which a reflection is detected, selecting a time window of each trace, each window having a time length which approximates the expected length of a seismic wavelet in said seismic traces;
- (d) detecting the presence of a seismic signal in the windows across said traces, said windows having time shifts from trace to trace corresponding with an assumed value of velocity;
- (e) repeating (c) and (d) for incremented values of assumed velocity centred on the velocity computed in (b); and
- (f) selecting the assumed value of velocity associated with the maximum seismic signal detected in step (d).

5. A method according to claim 4 characterised in that the assumed value of velocity in step (d) lies within a given range about the velocity computed in step (b).

6. A method according to Claim 4 or 5, characterised by the steps of:

- (g) for each CDP set storing the sum of the trace amplitudes along each travel time curve for which a reflection is detected; and
- (h) searching said amplitude sum along various assumed dip lines to determine the dip of the reflections at each of the zero offset sampling

the process of this invention, one computing system which is particularly suitable is supplied by the Control Data Corporation under the general model designation 6600.

In our Specification No. 1,282,936 we claim:— A method of determining the seismic velocity characteristics of the earth from a suite of seismograms representing the reflection of seismic energy from reflecting points in the earth, different seismograms of said suite of seismograms being obtained from respective detectors spaced along a line of exploration, comprising automatically processing said seismograms in a data processing machine as follows:

- (a) for a given value of vertical travel time T_0 , and assumed seismic velocity V , generating in said data processing machine physical representations of the corresponding travel time t_x for each of the traces in said suite of seismograms, said times t_x having time shifts from trace to trace corresponding with the assumed value of velocity;
- (b) for each value of t_x generated in step (a), selecting a respective window of each trace, said window commencing at t_x and having a time length which approximates the expected length of a seismic wavelet in said seismograms;
- (c) detecting the presence of a seismic signal in the windows across said traces;
- (d) repeating steps (a) to (c) in said data processing machine for different values of assumed velocity V , and for different values of travel time T_0 .

In our Specification No. 1,304,248 we claim:— A method of processing seismic traces representing reflections of seismic energy produced from a plurality of spaced sources and reflected from subsurface interfaces, utilizing automatic computing apparatus, comprising detecting signals in each of a plurality of said traces along several travel time curves each computed for one of a range of assumed acoustic velocities, selecting the acoustic velocity corresponding to maximum detected signal and plotting the alpha numeric representation of the selected acoustic velocity upon a chart of horizontal earth surface distance *versus* record time.

WHAT WE CLAIM IS:—

1. A method of determining velocity from sets of seismic traces representing the reflections of seismic energy produced from a plurality of spaced sources and reflected from subsurface interfaces comprising the following steps each performed on automatic computing apparatus:

performing a first stage search by detection of signals at points on the seismic traces to determine the reflection times and acoustic velocity characteristic of the subsurface interfaces, and

performing a second stage search, by detection of signals in selected time windows in the seismic traces, for acoustic velocity at the reflection times determined in the first stage search and with a velocity range centred on the acoustic velocity determined in the first stage search.

2. A method according to Claim 1, wherein the sets are CDP sets, characterised in that the CDP traces are stacked and the first stage search includes storing the amplitudes of the stacking results at the reflection times determined in the first stage search, and searching said amplitudes along various assumed dip lines to determine the dip of the subsurface interfaces producing each of the detected reflections.

3. A method according to Claim 2, characterised in that the second stage search is performed with the dip determined in the first stage search.

4. A method according to any of claims 1 to 3, characterised in that the first stage search includes:

- (a) detecting reflections in CDP traces along hyperbolic travel time curves for different, iterated, zero offset sampling times;
- (b) computing the velocity associated with each travel time curve along which a reflection is detected;

and that the second stage search includes:

- (c) for each zero offset sampling time for which a reflection is detected, selecting a time window of each trace, each window having a time length which approximates the expected length of a seismic wavelet in said seismic traces;
- (d) detecting the presence of a seismic signal in the windows across said traces, said windows having time shifts from trace to trace corresponding with an assumed value of velocity;
- (e) repeating (c) and (d) for incremented values of assumed velocity centred on the velocity computed in (b); and
- (f) selecting the assumed value of velocity associated with the maximum seismic signal detected in step (d).

5. A method according to claim 4 characterised in that the assumed value of velocity in step (d) lies within a given range about the velocity computed in step (b).

6. A method according to Claim 4 or 5, characterised by the steps of:

- (g) for each CDP set storing the sum of the trace amplitudes along each travel time curve for which a reflection is detected; and
- (h) searching said amplitude sum along various assumed dip lines to determine the dip of the reflections at each of the zero offset sampling



times for which a reflection is detected.

5 7. A method according to Claim 6, characterised in that the time shift from trace to trace of step (d) is a function of the dip determined in step (h) as well as of the assumed value of velocity.

10 8. A method of determining velocity from a set of seismic traces, substantially as herein described with reference to the accompanying drawings.

9. A method according to any preceding

Claim including the provision of a record of acoustic velocities determined in the second stage search.

15 10. A record of seismic velocities produced by the method claimed in claim 9.

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